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After five years' application of the European Union monitoring, reporting, and verification (MRV) mechanism: Review and prospectives

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Abstract

The global shipping sector is a major generator of greenhouse gas (GHG) emissions. In 2018, to reduce emissions, the European Union (EU) implemented a monitoring, reporting, and verification (MRV) system for large ships using EU ports. The MRV system has been functional for five years, with four years of data available as of May 2023. Despite this, the MRV data have not been fully explored, particularly in terms of analyzing the temporal trends of key parameters in MRV reports and evaluating the emission performance of shipping companies during the MRV implementation period. To address these gaps, this study analyzes MRV data collected from 2018 to 2021, investigating trends in ship's basic information, emissions monitoring methods, and energy efficiency. A case study of five shipping companies is conducted to evaluate their carbon emission performance, which highlights the impact of the coronavirus disease 2019 (COVID-19) pandemic on the industry. Furthermore, this study proposes policy recommendations and management strategies based on the data analysis results; these include facilitating collaboration and knowledge sharing, investing in green shipping infrastructure, and adopting accurate monitoring methods. These recommendations can guide policymakers and industry stakeholders to improve the MRV system and promote a more sustainable shipping industry in the EU and worldwide.

Keywords

Green shipping management, ship energy efficiency, monitoring, reporting, and verification (MRV) regulation, ship emissions, emissions monitoring methods, green shipping strategies

1. Introduction

Shipping is a vital component of the global supply chain, enabling international trade and contributing to globalization. In 2020, ships were responsible for over 80% of global merchandise trade, amounting to 10.9 billion metric tons in volume (UNCTAD, 2020). However, due to the shipping industry's reliance on fossil fuels, large amounts of GHGs, e.g., carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), and ozone (O_3), and pollutants, e.g., sulfur oxides (SO_x) and nitrous oxides (NO_x), are released into the atmosphere. These emissions not only exacerbate global warming but also lead to ocean acidification and air pollution. According to the Fourth International Maritime Organization (IMO) GHG Study, the international maritime industry was responsible for approximately 2.76% of GHG emissions in 2012, and this value increased by 4.70% in 2018 (IMO, 2020). The percentage is predicted to rise to 18% by 2050 if no measures are adopted (Rahim et al., 2016).

According to the initial IMO GHG Strategy, by 2050 the IMO aims to halve annual GHG emissions from global shipping compared with their levels in 2008 (IMO, 2018a). To achieve this target, the IMO is actively seeking to reduce GHG emissions from international shipping through various measures. One is the Energy Efficiency Design Index (EEDI) (IMO, 2011), a technical standard that establishes CO_2 emissions limits for new ships. Another measure implemented by the IMO is the Ship Energy Efficiency Management Plan (SEEMP) (IMO, 2011). This plan mandates that ship owners and operators create and execute strategies to enhance the energy efficiency of their ships. Furthermore, the IMO promotes the adoption of alternative fuels such as biofuels and hydrogen, as well as electric power, to minimize the shipping industry's carbon footprint[1]. The EU, an active participant in the IMO, also seeks to address climate change and achieve a carbon-neutral economy by 2050 (European Commission, 2019). To achieve these goals, the EU has implemented several initiatives. One encourages the use of alternative fuels and improved energy efficiency measures for existing vessels. Additionally, the EU has implemented a mandatory MRV system, which applies to vessels over 5,000 gross tonnage that enter, leave, or operate in the ports of EU member states. The MRV system allows the EU to gather accurate information about large ships by monitoring their fuel consumption, CO_2 emissions, distance traveled, time spent at sea, details of cargo carried, transport work, and average energy efficiency. These

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[1] https://www.imo.org/en/MediaCentre/HotTopics/Pages/Cutting-GHG-emissions.aspx.

comprehensive data can be used to incentivize energy efficiency enhancements and facilitate sustainable shipping practices within the EU, ultimately reducing the shipping industry's environmental impact and contributing to the EU's climate goals (EU, 2015).

Established under EU Regulation 2015/757 (EU, 2015), the MRV system involves several key steps. First, the shipping company develops a monitoring plan that outlines its approach to monitoring and reporting CO_2 emissions and other relevant data for each ship exceeding 5,000 gross tonnage; this plan must be submitted to an accredited verifier for assessment and approval. Upon approval, the shipping company is responsible for collecting data on the fuel consumption, CO_2 emissions, and transport work of the vessels in its fleet, in accordance with the approved monitoring plan. Following the reporting period, an emission report must be compiled, independently verified for accuracy and compliance, and then submitted to the European Commission and the relevant flag state authorities. The EU publishes a list of compliant ships and anonymized data on their emissions and efficiency, encouraging transparency and accountability within the maritime transport sector. By implementing this framework, the EU pursues a more sustainable maritime transport sector and contributes to the broader global efforts to combat climate change.

The EU has released MRV data for the 2018–2021 period, which are publicly available on the website of the European Maritime Safety Agency (EMSA). Despite their availability, few studies have analyzed the key parameters of MRV data, but this is essential to understand the effectiveness of the MRV system and identify areas for improvement. A study conducted by Yan et al. (2023) compared and analyzed the MRV data for 2018 and 2019, highlighting the need for further research in this area. However, due to data limitations, their study did not investigate the temporal trends of the key parameters covered by the MRV data. The analysis of temporal trends can provide valuable insights into the changes in energy efficiency and CO_2 emissions of ships calling at EU ports since the launch of the MRV system, helping to determine whether the MRV system promotes the decarbonization of shipping and assists in the achievement of the EU's emissions reduction targets. Moreover, there is limited research on the impact of the MRV system's implementation on company fleets' carbon emissions.

To address the above gaps, this study first conducts an in-depth analysis of the emission reports acquired by the MRV system between 2018 and 2021 (encompassing the latest release as of March 2023), examining trends in ship's basic information, emissions monitoring methods and results, and ship energy efficiency. Additionally, we conduct a case study of five shipping companies to examine the improvements in the CO_2 emissions of their vessels during the implementation of the MRV system. For each shipping company, the case study investigates in detail the differences in annual CO_2 emissions per distance for two consecutive years, utilizing the Wilcoxon signed-rank test. This study contributes to our understanding of the MRV system and its impact on the shipping industry.

This study provides valuable insights into the MRV system's impact on the shipping industry and its efforts to reduce carbon emissions. Through a comprehensive analysis of MRV data collected from 2018 to 2021, we highlight several key trends in ships' basic profiles, CO_2 emissions, and energy efficiency. Specifically, the study identifies the impact of the COVID-19 pandemic on the shipping industry by highlighting the decline in the number of ships of different types recorded in the MRV system between 2019 and 2020, with passenger ships being the most affected. In addition, declines in annual fuel consumption and CO_2 emissions are identified, as evidenced by a decreasing percentage of ships with high fuel consumption and CO_2 emissions over time. This finding indicates progress toward reducing the industry's carbon footprint. Furthermore, as of 2015, ships in sulfur emission control areas (SECAs) are required to utilize marine fuels with a maximum sulfur content of 0.1% (IMO, 2008); as of 2020, ships outside SECAs must limit the sulfur content of their fuel oil to a maximum of 0.5% (IMO, 2016). These increasingly stringent sulfur emissions regulations resulted in a significant decrease in heavy fuel oil usage in 2020, alongside a surge in light fuel oil consumption. This shift suggests that the industry is gradually transitioning toward more sustainable fuel options. With regard to ships' energy efficiency, the decline in the mean value of their annual average CO_2 emissions per distance in the first two years following the MRV system's implementation was interrupted by the COVID-19 pandemic, followed by a substantial increase in this value in 2021.

In addition to analyzing MRV records, we present case studies of five shipping companies: Mediterranean Shipping Company S.A. (MSC), Maersk, Hapag-Lloyd AG (HL), CMA CGM, and Hafnia Limited (Hafnia). Using the Wilcoxon signed-rank test, the results show that the technical measures implemented by the MSC, Maersk, and CMA CGM result in a significant decrease in their fleets' annual average CO_2 emissions per distance from 2018 to 2019. However, the annual average CO_2 emissions per distance for MSC, CMA CGM, Maersk, and HL increase substantially in 2021. This shift is attributed to vessels' longer port calls and delays caused by disruptions to the global supply chain by the COVID-19 pandemic, as ships had to travel at higher speeds to meet the increasing demand for seaborne cargo in 2021. In contrast, Hafnia's annual average CO_2 emissions per distance do not significantly change in 2021, because Hafnia mainly operates oil and chemical tankers, which are less susceptible to disruptions.

Finally, this study provides three policy recommendations and management strategies to promote a more sustainable shipping industry in the EU. These recommendations include facilitating collaboration and knowledge sharing among industry stakeholders, investing in green shipping infrastructure development, and offering incentives to encourage the adoption of more accurate fuel consumption and emissions monitoring methods. These measures can help to improve data reliability, environmental performance, and regulatory oversight in the shipping industry, ultimately leading to greater sustainability.

2. Literature Review

The MRV system is a key measure implemented by the EU to tackle GHG emissions from maritime transport (Psaraftis and Woodall, 2019). The system requires ship owners to monitor, report, and verify their ships' CO_2 emissions, with the aim of providing accurate information on emissions and incentivizing energy efficiency improvements (Panagakos et al., 2019). In this study, we divide the relevant literature into two categories: qualitative and quantitative. The qualitative literature has mainly discussed the potential impacts of implementing the MRV system on the shipping industry and examines the technical details of the MRV system. Akoel and Miler (2019) examined the MRV system's economic and operational effects on maritime transport, asserting that the MRV system is a cost-effective and environmentally efficient policy. Nelissen and Faber (2014) discussed the costs related to the deployment of the MRV system and estimated that the MRV system could reduce CO_2 emissions by at least 2% by 2030. Wang et al. (2020) highlighted three advantages of the MRV system: encouraging the use of fuel-efficient ships, incentivizing investments in emissions reduction technologies, and enabling ship owners to improve the efficiency of ship operations according to historical data. Additionally, some research has focused on the technical details of the MRV system. Sanabra and Borén (2020) explored 11 techniques to calculate ship emissions, dividing them into theory-based methods (TBMs) and ship-based methods (SBMs). TBMs cannot achieve MRV monitoring; SBMs comply with the MRV specifications, but some of the SBMs methods require greater onboard investment. Faber et al. (2013) compared four CO_2 emissions monitoring methods adopted in the MRV system in terms of equipment needs, costs, monitoring quality, and resulting emissions reduction incentives.

The quantitative literature has evaluated the effect of implementing the MRV system or analyzed the status of ship CO_2 emissions based on the emission reports issued by the MRV system. Based on data collected through a questionnaire completed by maritime experts, Rony et al. (2019) examined the effect of implementing the MRV system on current energy efficiency practices in the maritime industry. The authors also identified the potential challenges related to the robustness and quality of the data collected. Panagakos et al. (2019) evaluated the MRV regulations by computing energy efficiency indicators using operational data from 1,041 dry bulk carriers, revealing that the MRV system's geographical coverage limitations lead to considerable bias and hinder decision-making. Mannarini et al. (2020) augmented the CO_2 emissions data obtained from the MRV system for Ro-Pax vessels with three additional databases and assigned geographical coordinates to each vessel. Based on the augmented dataset, they analyzed various energy efficiency indicators for different vessel clusters and identified continental patterns in Ro-Pax emissions. Moreover, Mannarini et al. (2022) examined the effects of the COVID-19 pandemic on shipping emissions in Europe by utilizing both port call data and CO_2 emissions data of ferries in the MRV system. Their study found that unitary emissions decreased in 2020, and greater reductions were observed for older and larger ferries. Yan et al. (2023) compared the MRV data obtained in 2018 and 2019 and developed a prediction method based on gradient boosting regression tree (GBRT) to predict annual average fuel consumption by ship type. They also mentioned that other machine learning methods, such as neural network models (Stamenkovic and Vladimir, 2015), can be implemented for obtaining more accurate predictions in such tasks. In addition, the European Commission's annual report presents the ship basic information, sailing voyage information, and technical energy efficiency of fleets monitored in 2018 and 2019 based on MRV records (European Commission, 2021).

Based on the above, the qualitative literature on the EU MRV system has provided comprehensive analyses of the impacts of MRV implementation on the shipping industry, and some studies have explored the technical details of MRV. A few quantitative studies have analyzed the annual emission reports provided by the MRV system. These studies have mostly examined a single type of ship (Ro-Pax vessels or ferries) based on a single year's MRV data. To the best of our knowledge, only Yan et al. (2023) and the annual report of the European Commission (European Commission, 2021) compared two years of MRV data and thoroughly analyzed the key parameters of MRV records. However, the MRV mechanism has been operating for five years, and four years of MRV data have been accumulated as of May 2023. Few studies have investigated the temporal trends of key parameters in MRV reports. Furthermore, few studies have assessed the emission performance of shipping companies during the MRV implementation period. To address these gaps, we analyze the annual trends of MRV data based on MRV reports collected from 2018 to 2021. Then, we adopt the Wilcoxon signed-rank test to examine the differences in annual CO_2 emissions per distance for five shipping companies over two consecutive years. Finally, based on the findings, we provide some policy recommendations and management strategies to improve the MRV system and facilitate the decarbonization of the shipping industry.

3. Analysis of trends in ship-related features in the MRV system

As of 2018, all ships that call at any EU port must submit an annually aggregated emission report, which can be downloaded through a dedicated system named THETIS-MRV[2], supported by the EMSA. The data collected from the annual emission reports of the previous year are made available to the public no later than July 1 of the current year. The MRV data of 2018 were first released on June 30 2019, and four years of MRV data have been collected as of May 2023. In each year from 2018 to 2021, a total of 12,155, 12,134, 12,045, and 12,213 ships, respectively, submitted annual reports to the MRV system. Based on the four-year data, we analyze the annual trends in MRV records in terms of three aspects: the ship's basic profile, its emissions monitoring methods and results, and its energy efficiency.

3.1 Analysis of trends in ship's basic information in the MRV system

In the analysis of trends in ship's basic information, two factors, namely ship type and ship flag state, are taken into consideration. We first plot the types of vessels visiting EU ports from 2018 to 2021, as shown in Figure 1. As can be seen, 15 types of ships report their emissions to the EU MRV system, and the top five ship types are the same across all years: bulk carriers, oil tankers, container ships, chemical tankers, and general cargo ships.

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[2] https://mrv.emsa.europa.eu/#public/emission-report.

Furthermore, this research examines the MRV data obtained from 2018 to 2021, a period that includes the COVID-19 pandemic (from the end of 2019 to 2021). Therefore, we calculate the percentage decline in the number of ships of all types calling at EU ports in 2020 compared with 2019, as shown in Figure 1.1. This allows us to identify the trends and patterns in the number of ships of different types. According to the EMSA (2021), the COVID-19 pandemic severely impacted global shipping, with restrictions on passenger and crew movement hindering the operation of passenger ships. According to Figure 1.1 (which is located at the upper-right corner of Figure 1), the types of ships most affected in terms of the reduction in the number of visits are passenger ships, roll-on/roll-off (Ro-Ro) ships, container ships, and bulk carriers. This finding is in line with the EMSA's conclusion. It also indicates that the pandemic more strongly affected passenger ships than cargo ships.

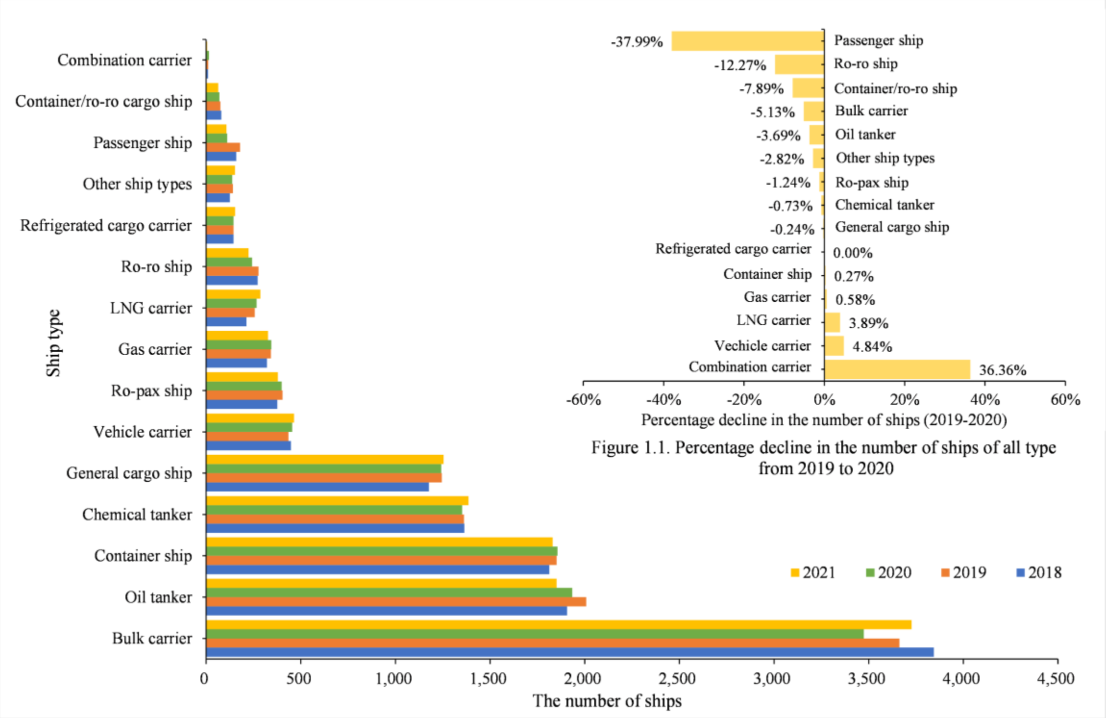

Figure 1. The ship type reported to the MRV regime

Before analyzing the flag states of the ships recorded in the MRV system from 2018 to 2021, we first search for the flag state of each vessel in the MRV system based on their IMO number, obtained from the Shipping Intelligence Network[3]. Then, we determine the 10 flag states with the highest number of ships recorded in the MRV system from 2018 to 2021, and the results are shown in Figure 2. During this period, the top eight flag states remain unchanged; they are Libera, the Marshall Islands,

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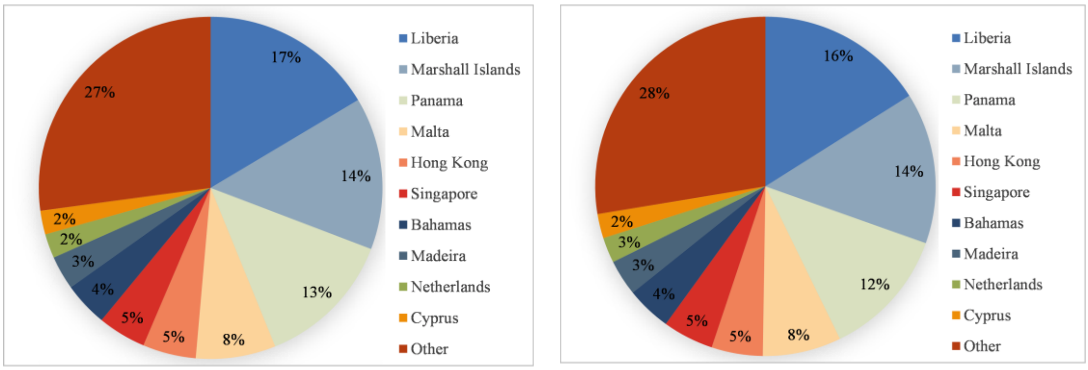
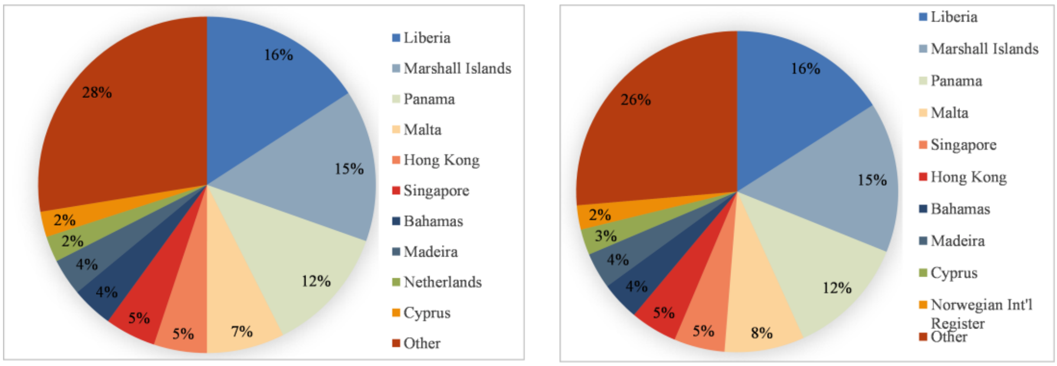
[3] https://www.clarksons.net/.

Panama, Malta, Hong Kong, Singapore, the Bahamas, and Madeira. The two lowest-ranked flag states from 2018 to 2020 are the Netherlands and Cyprus; however, in 2021, they are replaced by Cyprus and the Norway International Register (Norway).



(a) The distribution of ship flag states in 2018

(b) The distribution of ship flag states in 2019

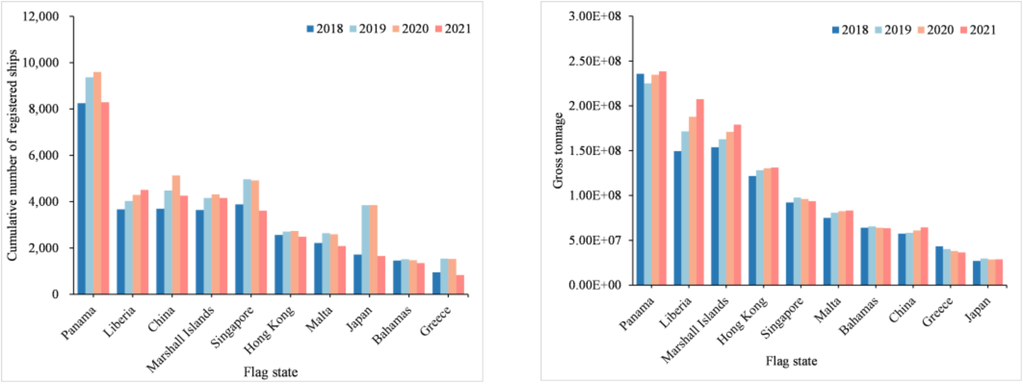


(c) The distribution of ship flag states in 2020

(d) The distribution of ship flag states in 2021

Figure 2. The distribution of ship flag states from 2018 to 2021

Furthermore, Lloyd’s List Intelligence provides the top 10 flag states in terms of the total number of registered vessels (above 500 gross tonnage) on an annual basis from 2018 to 2021 (Lloyd’s List, 2018, 2019, 2020, and 2021), as shown in Figure 3(a). In terms of the number of vessels recorded in the MRV system, most of the flag states in the top eight belong to the 10 flag states described above. However, although China, Japan, and Greece are ranked third, eighth, and tenth, respectively, in terms of the number of registered ships, they do not appear in the top 10 flag states in Figure 2. Although China, Japan, and Greece register more ships than some of the top 10 flag states (Figure 3(a)), such as Malta, the Bahamas, and Singapore, the gross tonnage of ships registered under these three flags is lower than that of ships registered for Malta, the Bahamas, and Singapore, as shown in Figure 3(b). Therefore, the number of ships over 5,000 gross tonnage in these countries is lower than in some of the top 10 countries listed in Figure 2. As the MRV system only collects emission reports from ships with a total tonnage exceeding 5,000, the number of ships reported by China, Greece, and Japan in the MRV system is not shown in Figure 2. In addition, Madeira, the Netherlands, Norway, and Cyprus report many vessels to the MRV, but these flag states are not ranked among the top 10 in Figure 3. The reason may be that these countries are within the EU and thus trade frequently with other member states; ships registered in these countries frequently call at EU ports and are thus recorded in the MRV system.



(a) Top 10 flag states in terms of the number of registered vessels

(b) Top 10 flag states in terms of the registered vessels' gross tonnage

Figure 3. Top 10 flag states by vessel count and gross tonnage from 2018 to 2021

3.2 Analysis of trends in ship emissions monitoring methods and results

We then analyze the trends in ship emissions monitoring methods and results. There are four monitoring methods currently available in the MRV system, namely (A) bunker fuel delivery note (BDN) and the periodic stocktakes of fuel tank; (B) bunker fuel tank monitoring on board; (C) flow meters for applicable combustion processes; and (D) direct CO_2 emissions measurements. Shipping companies can choose one or a combination of these monitoring methods to calculate each vessel's fuel consumption or CO_2 emissions.

The number and percentage of ships adopting each monitoring method from 2018 to 2021 are shown in Figure 4. The percentage of ships adopting method A remains above 40% from 2018 to 2021; due to this method's simplicity and cost-effectiveness, it is easily implemented by shipping companies. The percentage of ships adopting methods B and C is similar, and there is no significant change in the ratio of ships adopting these methods from 2018 to 2021. The reason for this finding may be that methods B and C can generate more accurate and detailed fuel consumption and emissions data than method A, but they may also be more expensive and complex to implement. In addition, method C is only applicable to vessels equipped with flow meters to monitor their combustion processes, and its implementation may not be feasible or cost-effective for all shipping companies. The number of ships using method D remains very low from 2018 to 2021, because method D is the most expensive to implement; indeed, it involves installing a continuous emissions monitoring system (CEMS) onboard to directly measure CO_2 emissions from the engine's exhaust gases (Faber, 2013).

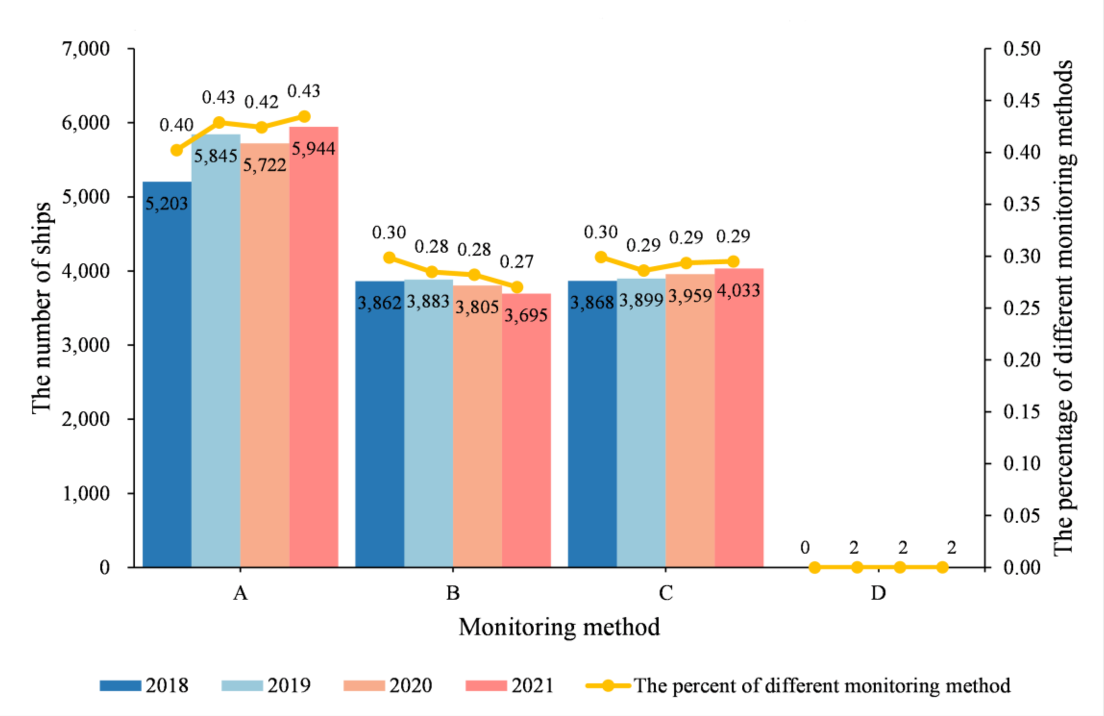


Figure 4. The distribution of ship monitoring methods from 2018 to 2021

To further examine the usage of different monitoring methods across different types of ships, we aggregate the ship data recorded in the MRV system from 2018 to 2021 and calculate the proportion of each type of ship using the different monitoring methods, as shown in Figure 5. We find that passenger ships, refrigerated cargo carriers, Ro-Pax ships, Ro-Ro ships, general cargo ships, container/Ro-Ro cargo ships, and combination carriers tend to use method A. Oil tankers, gas carriers, and vehicle carriers tend to use method B, while vehicle carriers, liquefied natural gas (LNG) carriers, and container ships tend to use method C.

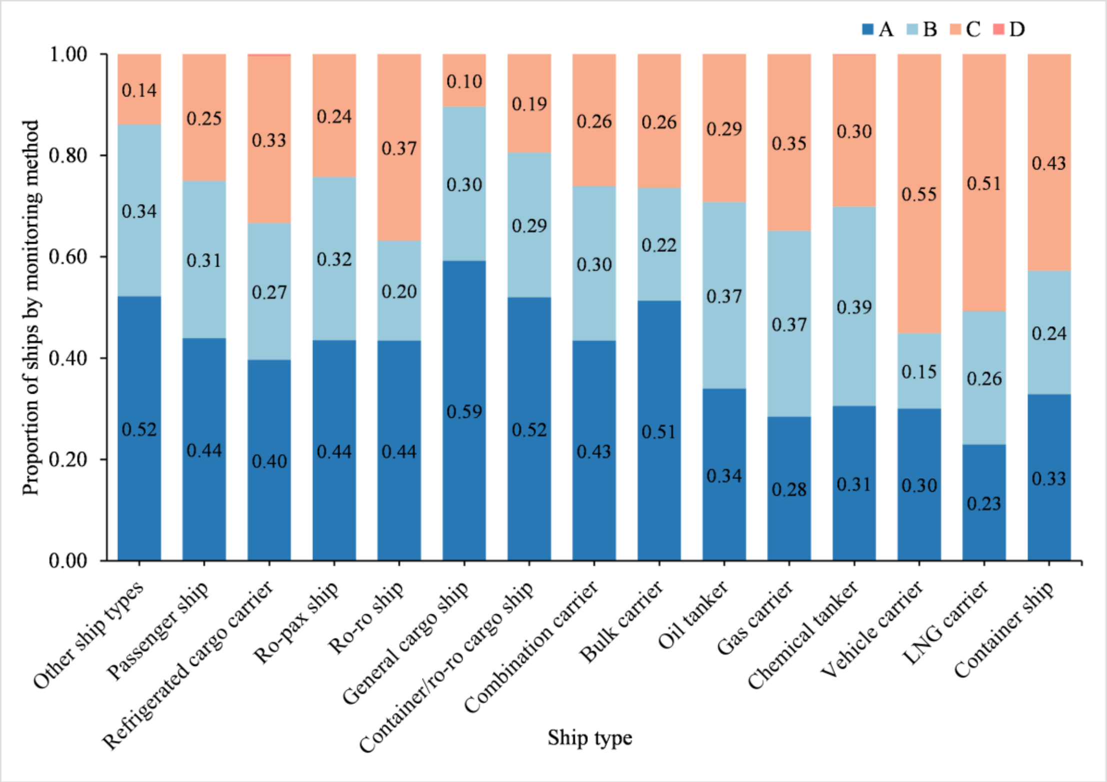


Figure 5. The distribution of monitoring methods used by ships of different types

In each year's MRV data, there are a small number of reports with zero annual total fuel consumption and zero total CO_2 emissions, which are outliers and are thus invalid. Figure 6 presents the number and percentage of invalid reports in each year's MRV data. It can be observed that the percentage of invalid reports decreases from 2018 to 2021, with a notable drop from 5.2% in 2018 to 2.7% in 2019, indicating that the quality of the MRV data is constantly improving. After removing all invalid reports and those with an abnormal magnitude[4] from the raw MRV data, the mean, median, and range of annual total fuel consumption are calculated, as shown in Figure 7. The mean and median values show a decline from 2018 to 2021. Moreover, the range value decreases from 57,566.9 mt in 2018 to 48,436.5 mt in 2019 and remains stable thereafter. This indicates a reduction in the differences in annual total fuel consumption among ships.

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[4] In the 2018 MRV data, one ship reported an annual total fuel consumption of 98,465.2 mt, making it the ship with the highest annual total fuel consumption in 2018. This ship consumed 40,889.84 mt more fuel than the ship with the second-highest fuel consumption in 2018, and its fuel consumption was also much higher than that of other ships with the highest annual total fuel consumption in 2019, 2020, and 2021. Therefore, the annual total fuel consumption of this ship is considered to be of an abnormal magnitude and is removed before calculating the median, mean, and range.

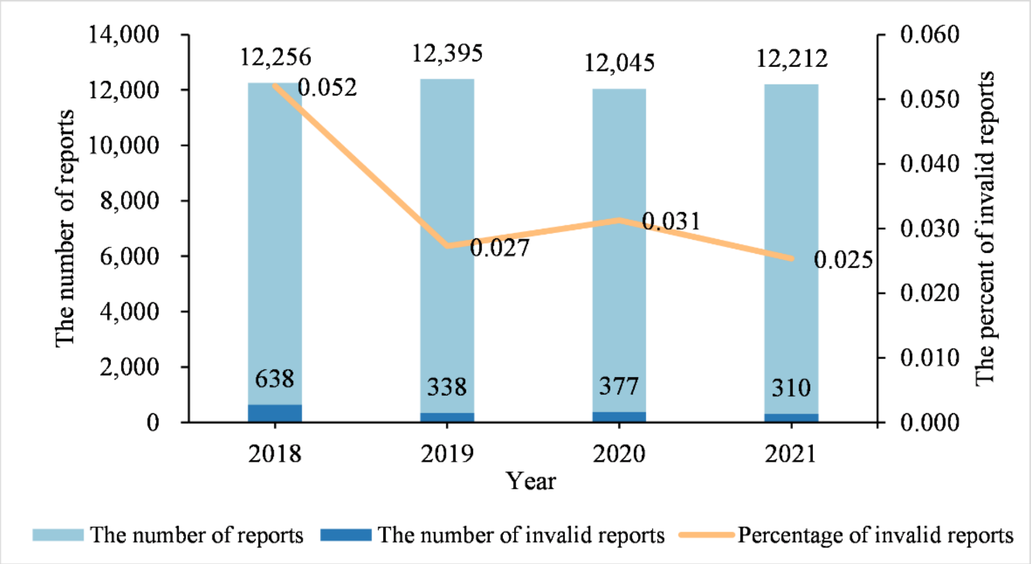

Figure 6. The number and percentage of invalid reports in the MRV regime from 2018 to 2021

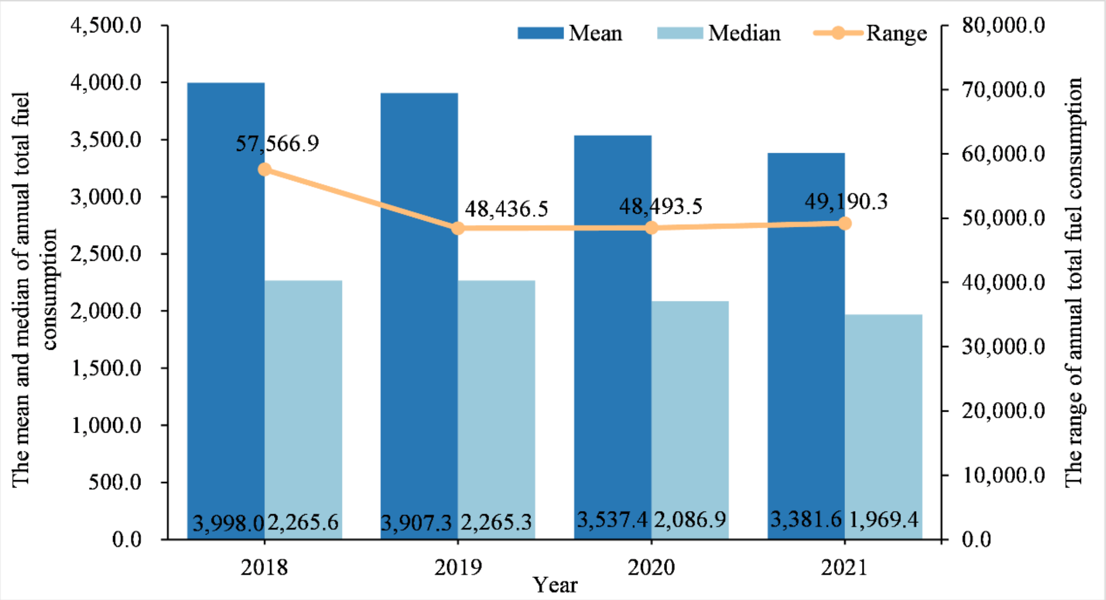

Figure 7. The mean, median, and range of annual total fuel consumption from 2018 to 2021

To gain a more comprehensive understanding of the annual total fuel consumption of ships, the total fuel consumption of each year is divided into multiple bins; we count the number of ships and calculate their percentage in each bin. The results are shown in Figure 8. It can be observed that the ships within different bins exhibit varying trends in annual total fuel consumption over time. First, the annual total fuel consumption of approximately 50% of the ships is less than 2,000 mt from 2018 to 2021. This percentage increases significantly over time, reaching 50.9% in 2021. Second, the annual total fuel consumption of less than 20% of the ships is between 2,000 mt and

3,000 mt during the studied period, with the percentage slowly increasing from 2018 to 2020, before returning to the 2019 level in 2021. Third, the percentage of ships in the (3,000, 4,000] and (4,000, 5,000] bins slowly decrease each year, with the percentage of ships in the (3,000, 4,000] bin not exceeding 12% and the percentage in the (4,000, 5,000] bin not exceeding 7% from 2018 to 2021. Last, the percentage of ships with annual total fuel consumption above 5,000 mt decreases yearly, falling below 20% in 2020. This decline can be attributed to the fact that fuel costs constitute a major proportion of a vessel's overall operating costs. In fact, fuel costs typically between 30% and 60% of a vessel's overall operating costs (Lashgari et al., 2021). As a result, ship operators must carefully plan their fleets' fuel consumption to reduce their operating costs, especially when fuel prices are high.

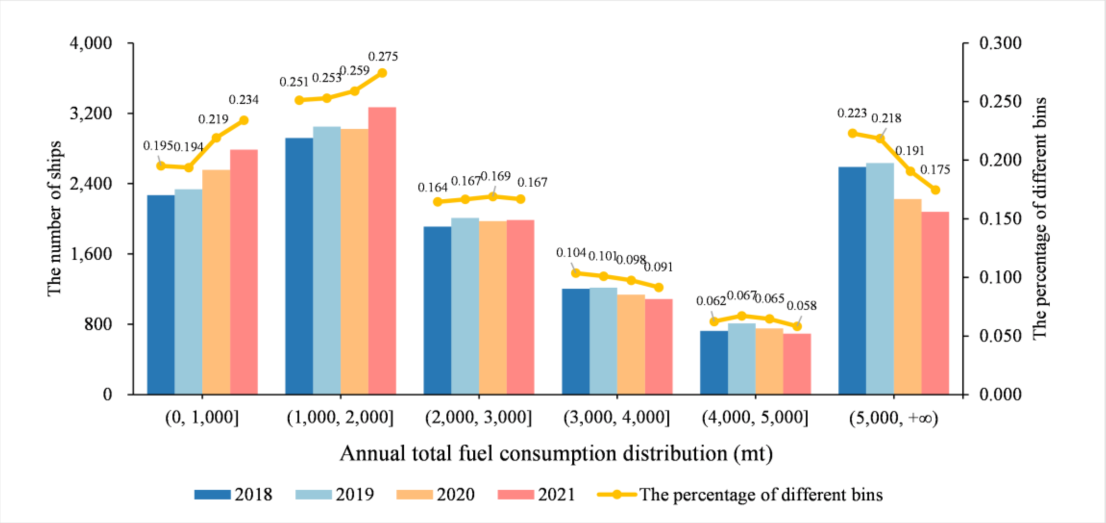

Figure 8. The distribution of annual total fuel consumption from 2018 to 2021

In line with the strong correlation between annual total CO_2 emissions and annual total fuel consumption, we observe a decrease in the mean and median values of annual total CO_2 emissions from 2018 to 2021, as illustrated in Figure 9. Furthermore, the range value decreases from 179,675.7 mt in 2018 to 151,784.0 mt in 2019, and remains stable thereafter.

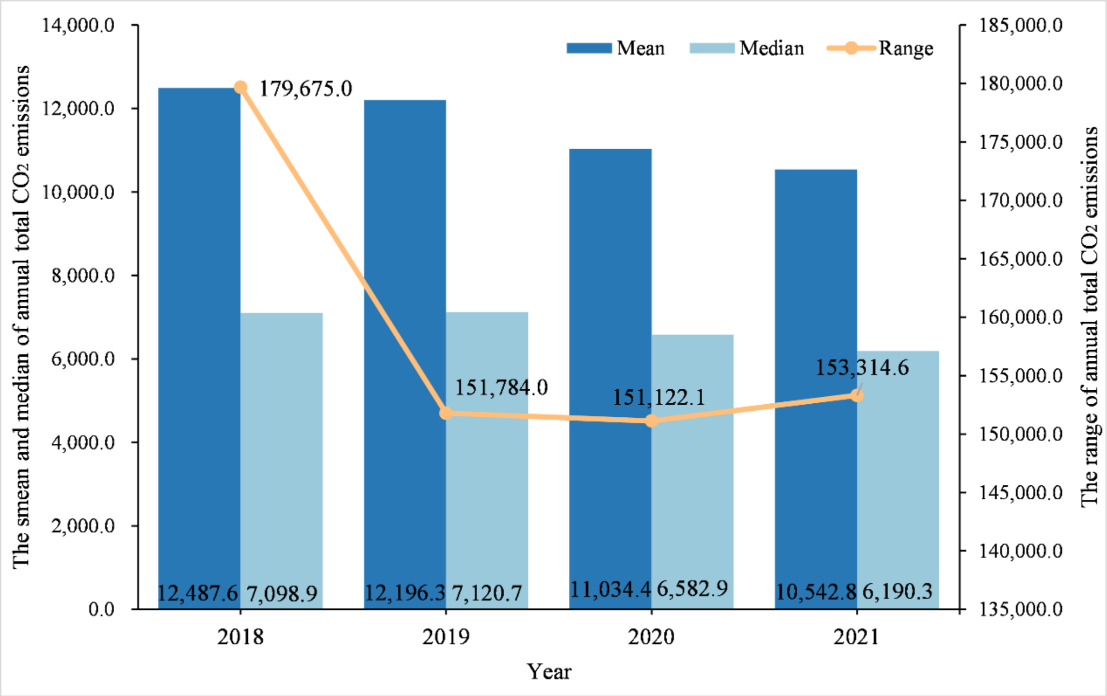

Figure 9. The mean, median, and range of annual CO_2 emissions from 2018 to 2021

Furthermore, ships are categorized into six bins in terms of their annual total CO_2 emissions, as illustrated in Figure 10. This shows that the annual total CO_2 emissions of over 60% of the ships recorded in the MRV system are below 10,000 mt, and this percentage increases annually, finally reaching 69.7% in 2021. Meanwhile, the ships in the (10,000, 15,000], (15,000, 20,000], and (20,000, 25,000] bins exhibit slow downward trends in annual total fuel consumption over time. Over 10% of the vessels produce over 25,000 mt of CO_2 per year from 2018 to 2020, and this percentage significantly decreases annually, reaching 9.6% in 2021. This phenomenon might be associated with the increasingly stringent emissions requirements set by the IMO. In 2018, the IMO set the goal to reduce GHG emissions from global shipping by a minimum of 50% by 2050, compared with 2008 levels. Additionally, it aims to reduce carbon intensity by a minimum of 40% by 2030 (IMO, 2020). To achieve these targets, the IMO has introduced short-term measures, including the Energy Efficiency Existing Ship Index (EEXI); for ships built before 2013 and exceeding 400 gross tonnage, ship owners must achieve a satisfactory EEXI value by 2023 (IMO, 2021a; Schroer et al., 2022). The Carbon Intensity Indicator (CII) applies to all Ro-Pax, cargo, and cruise ships; each ship must calculate and report its CII rating every year starting from 2023 (IMO, 2021b). Ships must achieve a C rating or above, and those that receive a D rating for three consecutive years or an E rating in any single year must submit a corrective action plan to be approved. Therefore, to comply with these regulations, shipping companies must take measures to improve their energy efficiency, such as retrofitting vessels with more efficient engines, optimizing propellers, and optimizing speeds and routes, and must consider using alternative fuels such as LNG to reduce their CO_2 emissions (Ančić et al., 2020).

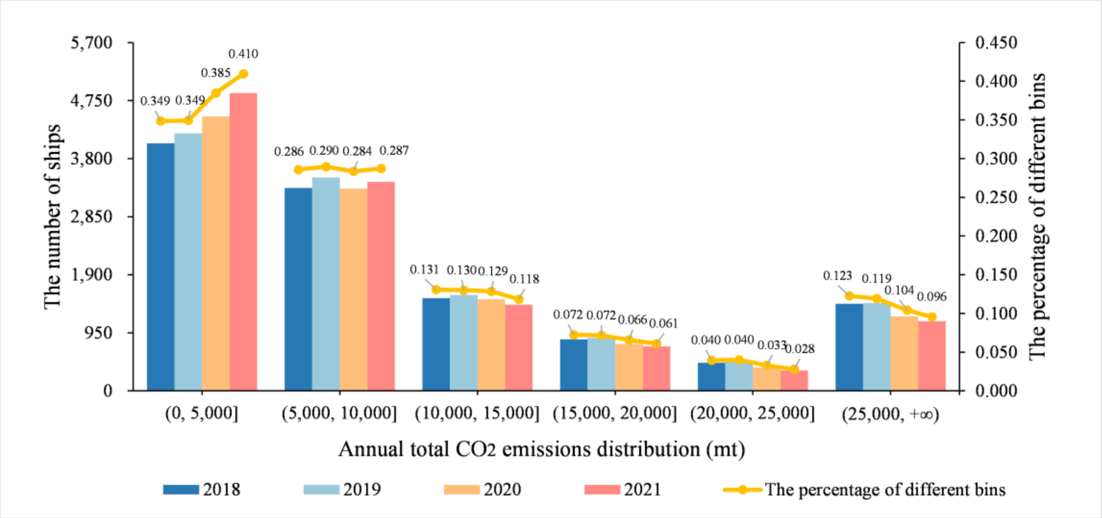

Figure 10. The distribution of annual total CO_2 emissions from 2018 to 2021

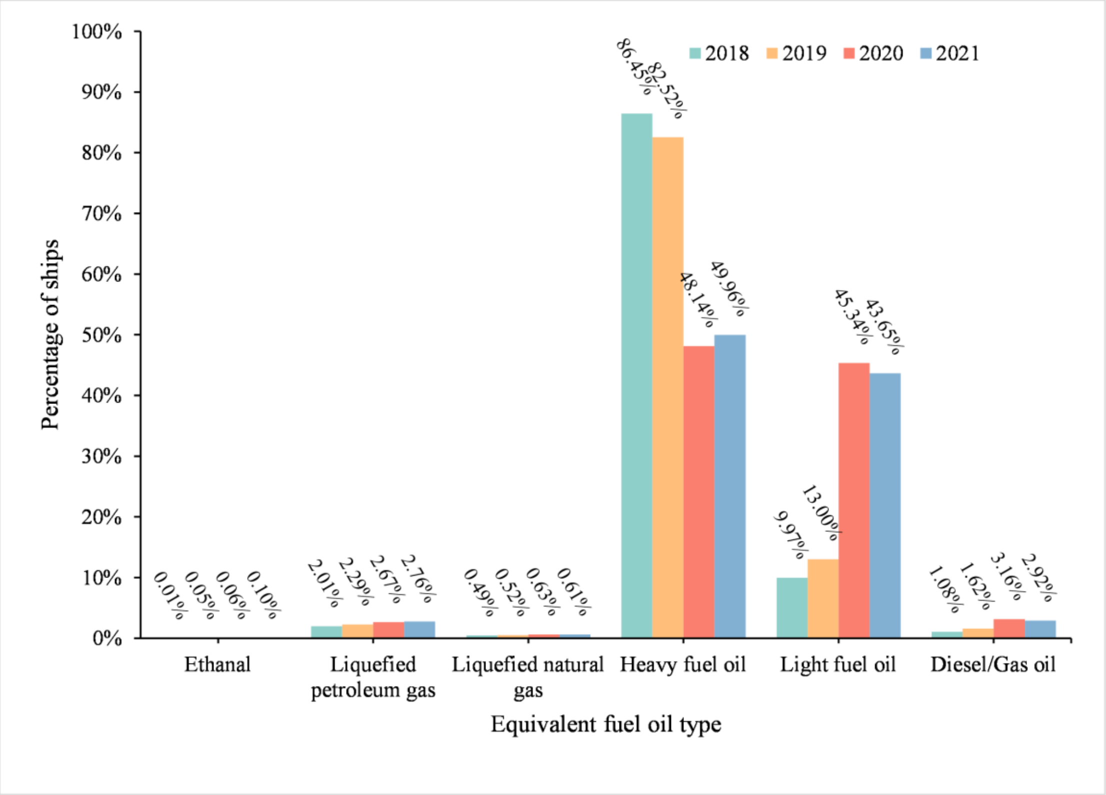

Figure 11. The distribution of equivalent fuel type consumed by ships

According to each ship’s annual total fuel consumption and CO_2 emissions, we further compute the CO_2 emissions produced by each unit of fuel consumed. This value is referred to as the carbon ratio of the ship. As shown in Table 1, different fuels have different emissions factors (i.e., the amount of carbon emissions generated by each unit of energy consumed or used) due to differences in their chemical compositions and combustion properties, so we can estimate the emissions factors of a ship based on the carbon ratio calculated. As ships use different types of fuels for different activities, the carbon ratio is not equal to a certain emissions factor; it is only an estimate of the emissions factor. Therefore, to infer the type of fuel used by a ship, we generate ranges for the carbon ratio. We can determine the equivalent fuel type used by the ship according to the range within which its carbon ratio falls, referring to Table 1. For example, when the carbon ratio falls within the interval $3.114, 3.151$, we can conclude that the ship uses heavy fuel oil. We plot the distribution of equivalent fuel oil types used from 2018 to 2021 in Figure 11. Over 90% of the vessels use light fuel oil and heavy fuel oil during this period, while the percentages of vessels that use other types of fuels are relatively small. Indeed, light fuel oil and heavy fuel oil are relatively cheap compared with other types of fuel oil. In addition, the adoption of cleaner fuels, such as LNG, ethanal, and liquefied petroleum, is restricted by factors such as the availability of infrastructure and the high costs of retrofitting or building new ships with engines that use these fuels (American Bureau of Shipping, 2020). For example, the availability of LNG bunkering facilities is limited in many regions around the world. According to Statistic[5], there were 23 ports offering LNG bunkering services in 2022, representing only 1.9% of over 1,200 seaports in the EU[6]. Furthermore, retrofitting a ship with an LNG propulsion system requires considerable modifications to the ship's existing system and its fuel storage facilities, costing tens of millions of dollars per vessel (Hapag-Lloyd AG, 2020).

It is worth noting that the percentage of vessels using heavy fuel oil significantly declines in 2020, while the percentage of vessels using light fuel oil sharply increases during the same period. In addition, the percentage of vessels that use clean-burning fuels, such as ethanal, liquefied petroleum gas, and diesel/gas oil, slowly increases from 2018 to 2021. These shifts can be attributed to the implementation of IMO regulations in 2020, requiring the maximum fuel sulfur content used outside SECAs to be 0.5% m/m (IMO, 2016), modifying the previous limits of 0.1% m/m within SECAs and 3.5% m/m outside SECAs (IMO, 2008).

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[5] https://www.statista.com/statistics/1103931/lng-bunkering-availability-in-ports-by-region/#statisticContainer.

[6] https://ec.europa.eu/commission/presscorner/detail/en/MEMO_13_448.

Table 1. Calculation of equivalent fuel oil type

(Equivalent) fuel oil type	Emissions factor	The range of carbon ratio
Diesel/Gas oil	3.206	$[3.206,\ +\infty)$
Light fuel oil	3.151	$[3.151,\ 3.206)$
Heavy fuel oil	3.114	$[3.114,\ 3.151)$
Liquefied petroleum gas	Propane: 3.000 Butane: 3.3030	$[3.000,\ 3.114)$
Liquefied natural gas	2.750	$[2.750,\ 3.000)$
Ethanol	1.913	$[1.913,\ 2.750)$

3.3 Analysis of trends in ship energy efficiency in the MRV system

Based on the annual average fuel consumption per distance (FCD) per vessel from 2018 to 2021, ships are categorized into seven bins, as shown in Figure 12. If the annual average FCD is listed as “divided by zero”[7], such ships are placed in the “not applicable” category. These ships gradually decrease from 2018 to 2021, indicating an improvement in the quality of the MRV data over the years. After removing all invalid values, the mean values of the annual average FCD from 2018 to 2021 are 137.02, 131.92, 132.43, and 187.92, respectively. The mean value decreases by 3.7% in 2019 but increases by 41.9% in 2021. This trend can be attributed to changes in sailing speed, as the mean value of the annual average sailing speed[8] decreases from 11.02 to 10.96 in 2019 and increases from 11.85 to 12.03 in 2021. Furthermore, we find that EU ports handle almost 3.5 billion metric tons of seaborne cargo in 2021, which is an increase of more than 4% compared with the previous year[9]. With the disruption to the global supply chain due to the COVID-19 pandemic, ships experienced longer port calls and delays in 2021. Therefore, ships were required to travel at higher speeds to meet the higher demand for seaborne cargo, resulting in an increase in the mean value of the annual average FCD from 2020 to 2021. In addition, in our data, the average annual fuel consumption of over 80% of the ships does not exceed 200 mt from 2018 to 2021, and the percentage of such ships increases annually. The proportion of vessels with average annual fuel consumption exceeding 400 mt is less than 1% during the same

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[7] Ships that report the annual average FCD as “divided by zero” report their annual time spent at sea as zero, and most of these ships report their total fuel consumption as zero.

[8] The average annual sailing speed of the ship is calculated by dividing the total sailing distance (in nm) by the annual total time spent at sea (in hours), where the total sailing distance is calculated based on the annual average FCD (kg/nm) and the total fuel consumption (mt).

[9] https://www.statista.com/statistics/1281738/gross-weight-seaborne-goods-european-union-ports/.

period. This indicates that the shipping industry is beginning to adopt more fuel-efficient practices.

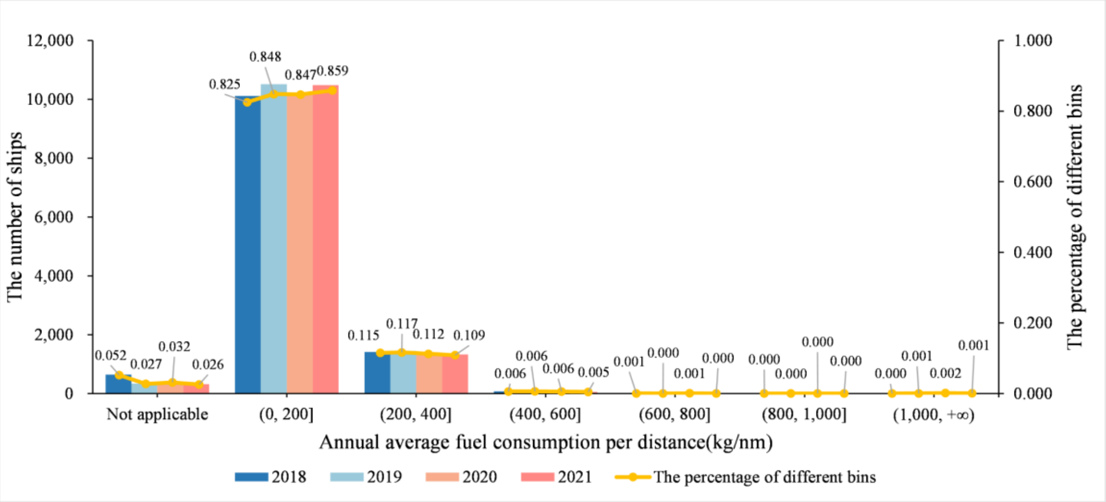


Figure 12. The distribution of annual average fuel consumption from 2018 to 2021

Based on their annual average CO_2 emissions per distance, we divide ships into seven bins, as shown in Figure 13. The variation in the number of ships whose values are “divided by zero” follows the same pattern as that observed in the annual average FCD. After removing all invalid values, the mean value of the annual average CO_2 emissions per distance for 2018 to 2021 is 427.99, 412.36, 414.60, and 592.23, respectively. The mean value of the annual average CO_2 emissions per distance decreases by 3.7% in 2019 compared with 2018 but increases by 42.8% in 2021 compared with 2020. The trend in the mean value of the annual average CO_2 emissions per distance is in line with the trend in the annual average FCD. This indicates that the disruption caused by the COVID-19 pandemic interrupted the improvement in ships’ CO_2 emissions, resulting in a significant decrease in their emissions reduction performance. In addition, from 2018 to 2021, over 80% of the ships have average annual CO_2 emissions of less than 600 mt, and the percentage increases annually. The percentage of ships with average annual fuel consumption exceeding 800 mt is below 10% during the same period. This indicates that ships using EU ports are navigating in an increasingly eco-friendly mode, thus fostering sustainable development in the shipping industry.

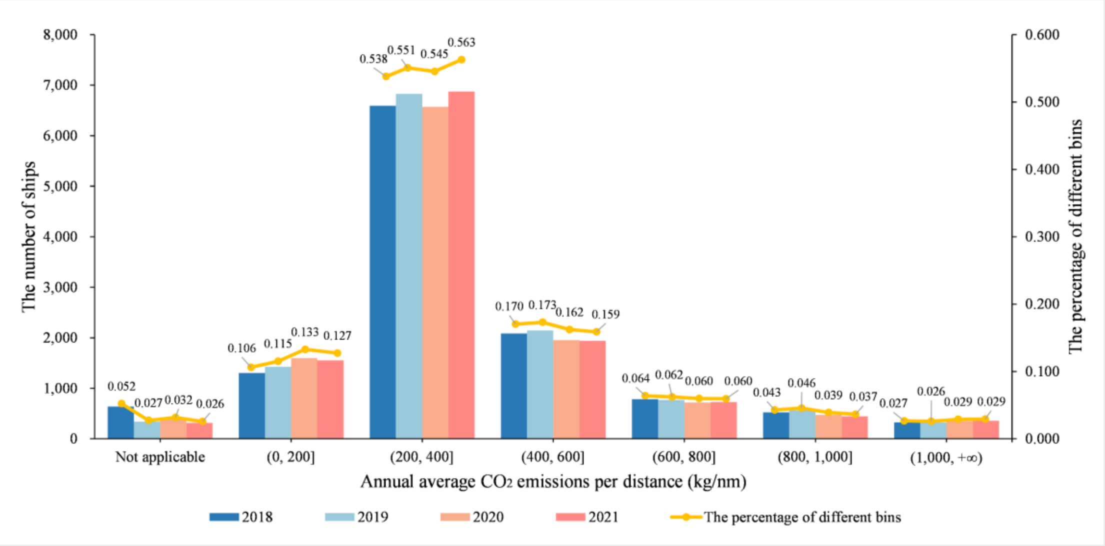


Figure 13. The distribution of annual average CO_2 emissions from 2018 to 2021

Finally, we examine the trends in ships' technical efficiency indicators as reported in the MRV system. According to EU Regulation 2015/757 (EU, 2015), ships that call at EU ports are required to monitor and report their technical efficiency indicators. In general, ships must report their attained EEDI in compliance with the International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI. Certain types of ships that fall beyond the scope of the EEDI report an estimated index value (EIV) instead. To analyze the temporal characteristics of ship technical efficiency indicators, we first filter ships that report the same indicators from 2018 to 2021 (i.e., those that report either the EEDI or EIV for all years between 2018 and 2021). In the MRV data, there are 956 ships reporting their EEDI and 3,261 ships reporting their EIV for the studied period.

Based on the selected ships reporting the same indicator, we categorize the temporal variations in technical efficiency into three types: stable trend, partial variation, and continuous variation. The stable trend can be further divided into three subcategories: no change, denoted by A1; a stable increase, denoted by A2; and a stable decrease, denoted by A3. Partial variation can be further divided into four subcategories: a decrease in the second year and stable thereafter, denoted by B1; an increase in the second year and stable thereafter, denoted by B2; no change in the first three years and a decrease in the fourth year, denoted by B3; and no change in the first three years and an increase in the fourth year, denoted by B4. Continuous variation can be further divided into two subcategories: first increasing and then decreasing, denoted by C1; and first decreasing and then increasing, denoted by C2.

After classifying ships according to the time-varying characteristics of their EEDI, the proportion of ships in each category is obtained, as shown in Figure 14. The temporal trends of subcategories A1, A2, and A3, following a stable trend, are shown in Figure 15(a); the temporal trends of subcategories B1, B2, B3, and B4, with partial variation, are shown in Figure 15(b); the temporal trends of subcategories C1 and C2, with continuous variation, are shown in Figure 15(c). The majority of ships (92%) are classified as A1, meaning that there is no change in the EEDI of most ships from 2018 to 2021. The reason for this finding is that the EEDI of a ship is determined by its design parameters and its use of energy-efficient technologies (IMO, 2018b), which are relatively fixed over a short period. In addition, retrofitting a ship with new, energy-efficient technologies or implementing design changes can be time-consuming and costly and are thus limited. Therefore, the EEDI of most ships does not change significantly over the studied period. For 4% of the ships, their EEDI shows a decreasing trend from 2018 to 2021, including ships classified as A2, B1, and B3; 3% of the ships show an increasing EEDI during the same period, including ships classified as A3, B2, and B4. This means that a small percentage of ships may use new, energy-efficient technologies or different designs to increase their technical efficiency, while a few ships possess aging or malfunctioning equipment that is not properly maintained.

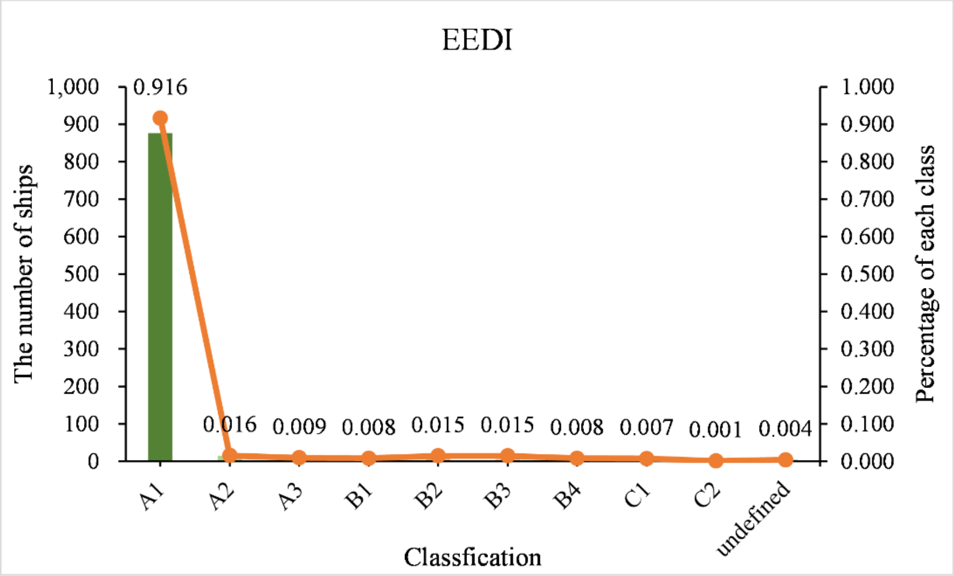
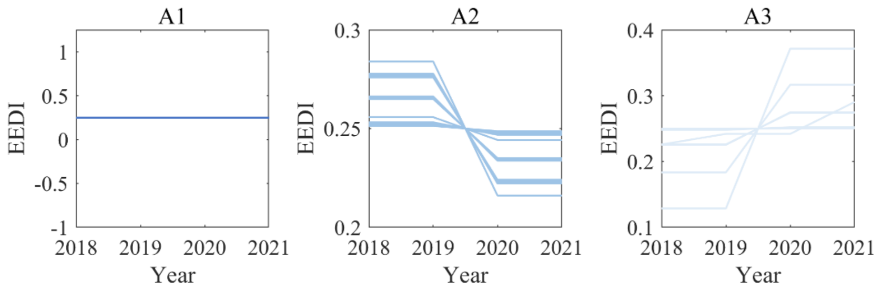
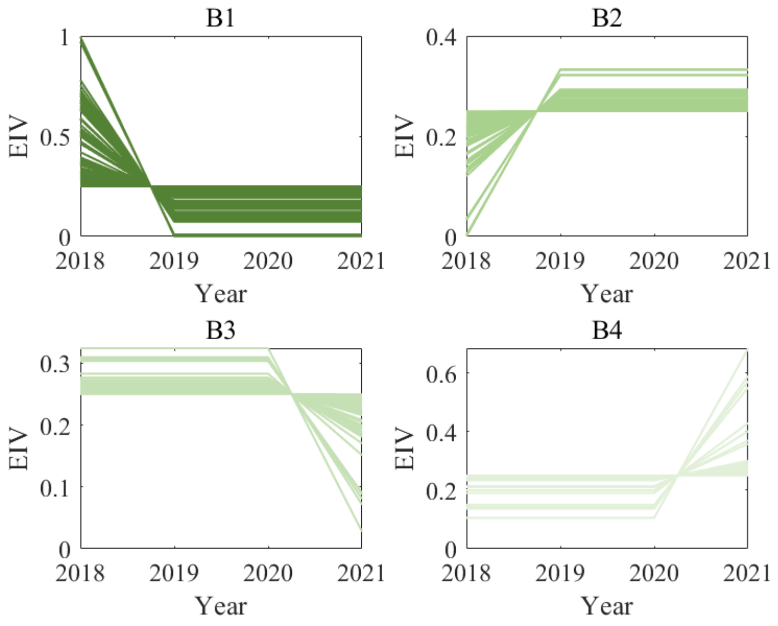


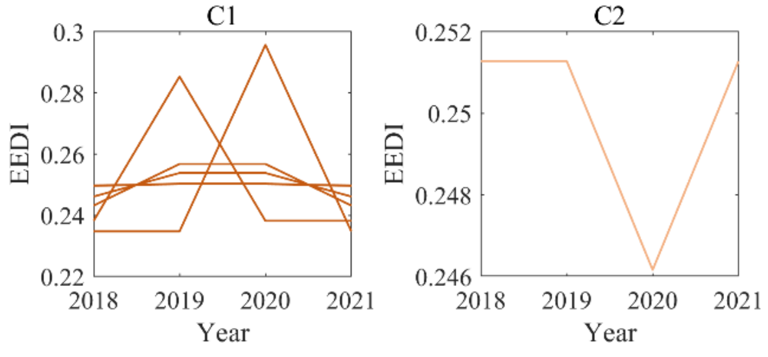
Figure 14. Classification results for ships reporting EEDI



(a) Steady trend



(b) Partial variation



(c) Continuous variation

Figure 15. The temporal trend of EEDI reported by ships

For ships reporting an EIV from 2018 to 2021, the proportion of ships in each category is shown in Figure 16. The temporal trends of the subcategories showing a stable trend, partial variation, and continuous variation are presented in Figure 17(a), 17(b), and 17(c), respectively. The majority of ships (71%) are classified as A1. This means that the EIV of most ships remains unchanged from 2018 to 2021. In addition, based on data from the Shipping Intelligence Network regarding the years in which ships are built, ships reporting their EIV have an average age of 17 years, while those reporting their EEDI have an average age of 7 years. This suggests that ships reporting the EEDI are relatively modern, and their owners, operators, and managers have invested extensively in their energy efficiency, leading to stable technical efficiency indicators from 2018 to 2021; most of these ships are classified as A1. In contrast, ships reporting the EIV are older and may have inferior operating conditions and maintenance levels than more modern ships. The fluctuation in their technical efficiency indicators may be more pronounced, and only 71% of these ships are classified as A1, which is lower than the proportion of A1 ships reporting the EEDI.

Similar to the EEDI, the EIV only considers the design and specifications of the ship and therefore does not change significantly in a short period, unless the ship is retrofitted. Moreover, 15% of the vessels exhibit a decline in their EIV, including those classified as A2, B1, and B3, which suggests that these ships have incorporated new, energy-efficient technologies or design changes to enhance their technical efficiency. Meanwhile, 7% of the vessels show an increase in their EIV, including those classified as A3, B2, and B4, which can be attributed to aging or malfunctioning equipment onboard.

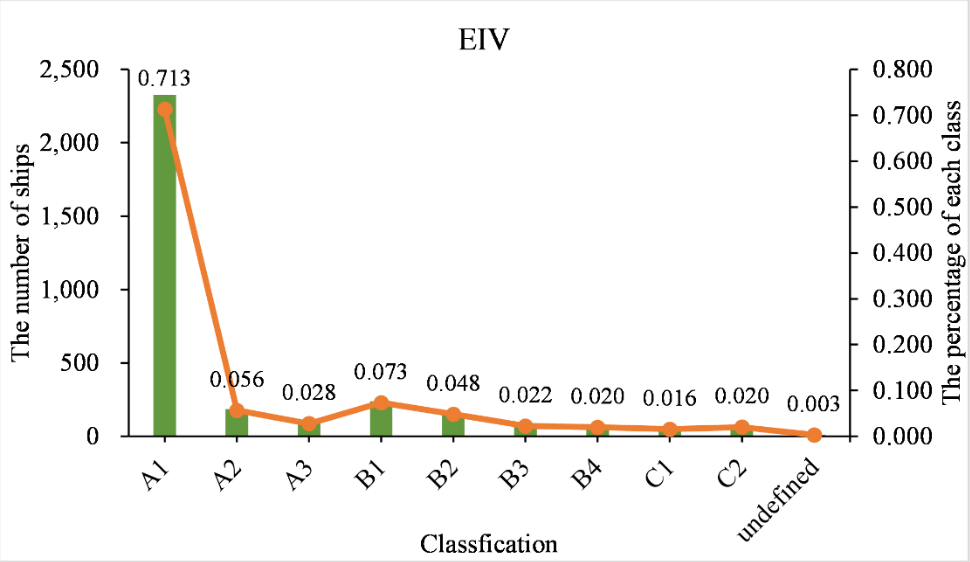
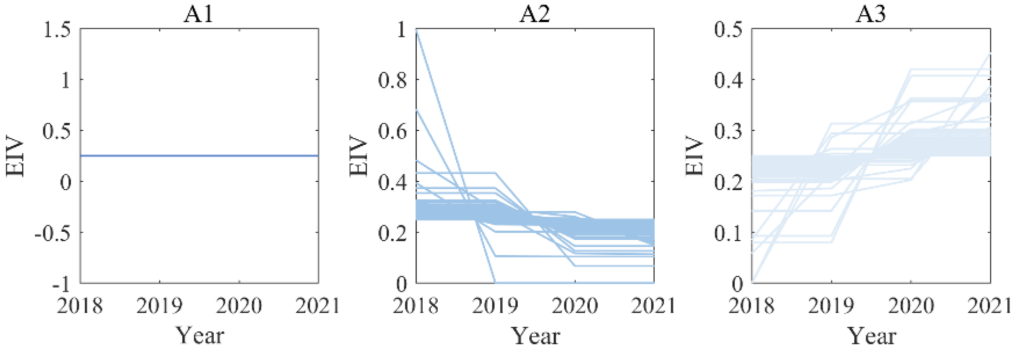
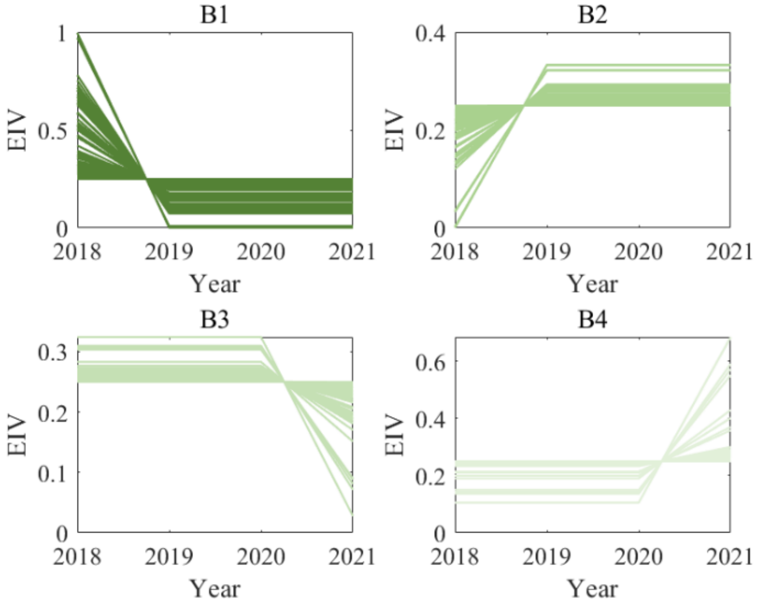


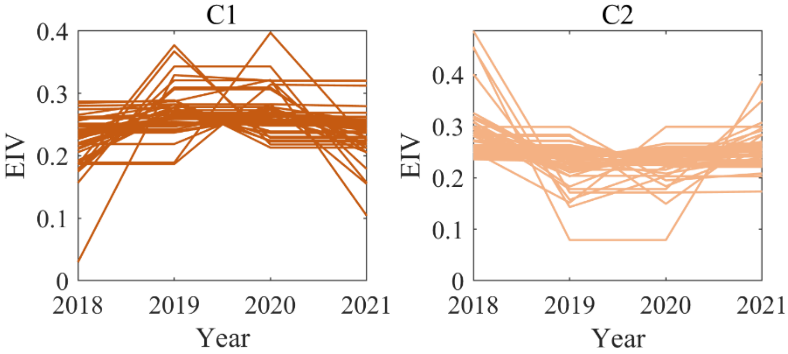
Figure 16. Classification results for ships reporting EIV



(a) Steady trend



(b) Partial variation



(c) Continuous variation

Figure 17. The temporal trend of EIV reported by ships

4. Case studies of five shipping companies

To explore whether shipping companies have optimized the carbon emissions of their vessels during the implementation of the MRV system, we evaluate their carbon emission performance based on their annual average CO_2 emissions per distance for ships reported by different companies in the MRV system. We also evaluate their carbon emission performance based on the companies' sustainability reports or annual reports. We first select ships recording their annual average CO_2 emissions per distance from 2018 to 2021 and identify the shipping companies that own them from the Shipping Intelligence Network database based on their IMO numbers. Then, we select the five shipping companies that report the largest numbers of ships to the MRV system and analyze their carbon emission performance. The five shipping companies are MSC[10], CMA CGM[11], Maersk[12], HL[13], and Hafnia[14], which have 286, 160, 148, 90 and 77 vessels reporting the annual average CO_2 emissions per distance from 2018 to 2021, representing 4.7%, 2.7%, 2.5%, 1.5%, and 1.3% of the total vessels selected.

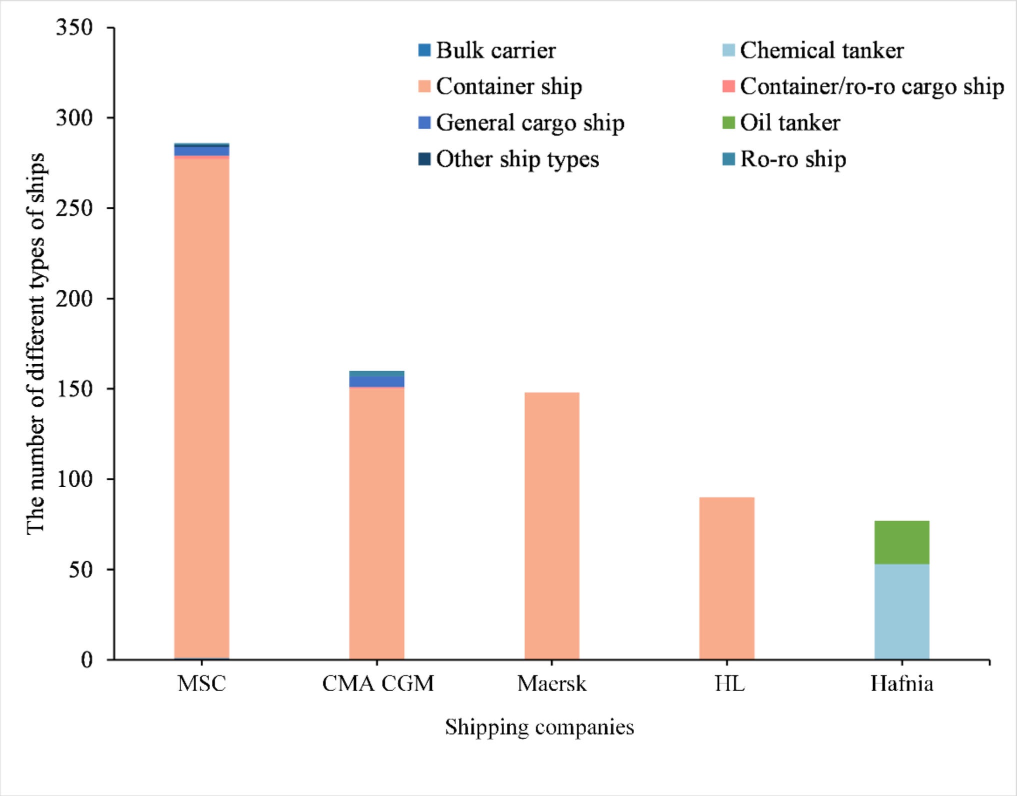


Figure 18. The number of different types of ships under the five shipping companies reporting the highest number of ships

We first analyze the number of different types of ships reported. Figure 18 indicates that the types of vessels reported by MSC, CMA CGM, Maersk, and HL are mainly container ships, which constitute 96.5%, 93.8%, 100%, and 100% of all vessels

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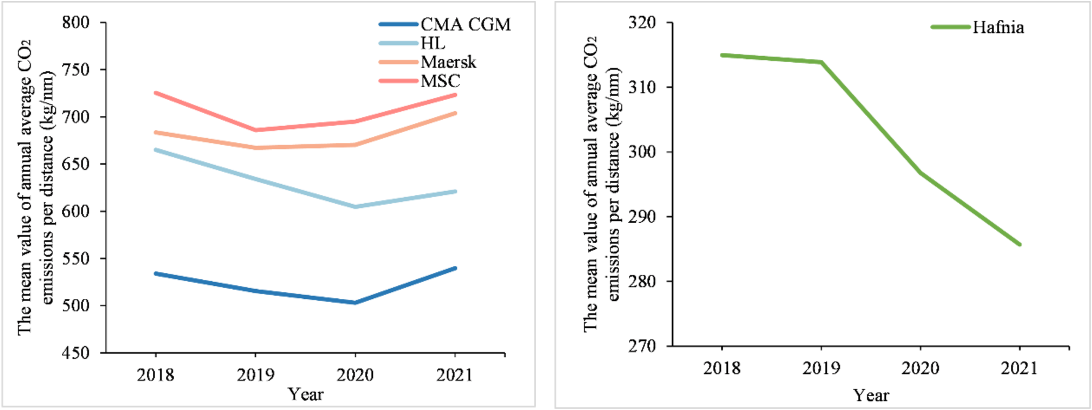
[10] https://www.msc.com/.
[11] https://www.cma-cgm.com/.
[12] https://www.maersk.com/.
[13] https://www.hapag-lloyd.com/en/home.html.
[14] https://hafniabw.com/.

reported, respectively. The vessels reported by Hafnia are chemical tankers and oil tankers, with chemical tankers accounting for 68.8% and oil tankers 31.2%. Then, we calculate the mean values of the annual average CO_2 emissions per distance from 2018 to 2021 for the fleets of the five shipping companies. Figure 19 shows that the mean values of the annual average CO_2 emissions per distance for the five shipping companies' fleets show a decline from 2018 to 2020. In addition, the mean values of the annual average CO_2 emissions per distance for the fleets of MSC, CMA CGM, Maersk, and HL increase from 2020 to 2021, while that for Hafnia's fleet decreases from 2020 to 2021, differing from the other four shipping companies.



(a) (b)

Figure 19. The temporal trend of the mean value of annual average CO_2 emissions per distance for the fleets of five shipping companies

Furthermore, to accurately determine whether the shipping companies have optimized the CO_2 emissions of their vessels, we use statistical methods to test whether there is a significant difference in their annual average CO_2 emissions per distance for two consecutive years. As the sample data do not follow a normal distribution and the paired differences are also not normally distributed, we use the Wilcoxon signed-rank test to assess whether the population mean ranks of the annual average CO_2 emissions for two consecutive years differ. The test results are shown in Table 2.

Table 2. The results of Wilcoxon signed-rank test for the five shipping companies

Shipping company	Paired years		
	2018–2019	2019–2020	2020–2021
MSC	$<0.001^{***}$	0.328	$<0.001^{***}$
Maersk	$<0.001^{***}$	0.170	$<0.001^{***}$
CMA CGM	0.007^{**}	0.003^{**}	$<0.001^{***}$
HL	0.251	$<0.001^{***}$	0.018^{*}
Hafnia	0.955	0.011^{*}	0.122

Note: "*" represents significance level of 0.05; "**" represents significance level of 0.01; "***" represents significance level of 0.001.

(1) MSC and Maersk

For MSC and Maersk, the annual average CO_2 emissions per distance of their ships in 2018 and 2019 are significantly different at the 0.05 level, there is no significant difference between 2019 and 2020, and there is a significant difference between 2020 and 2021.

The change in the annual average CO_2 emissions per distance for MSC and Maersk from 2018 to 2019 can be attributed to the measures taken by both companies to reduce their carbon footprints. Based on the sustainability reports provided by MSC (2018 and 2019), the company has adopted various measures to reduce its energy consumption and CO_2 emissions. These measures include recording and analyzing its ships' performance based on the Energy Efficiency Operational Indicator (EEOI) (Kanberoğlu and Kökkülünk, 2021), real-time ship performance monitoring, and vessel adaptation and enhancement. Similarly, Maersk has sought to optimize the energy efficiency of its fleet by adopting technical retrofitting measures, such as new bulbous bows, new propellers, and engine modifications (Maersk, 2018 and 2019). These measures help to reduce resistance and increase the propulsion efficiency of ships, resulting in lower fuel consumption and CO_2 emissions.

Although the annual average CO_2 emissions per distance in 2020 and 2021 are significantly different, the underlying reasons for the change differ from those in the case of 2018–2019. In 2021, COVID-19 led to a significant increase in transportation demand from MSC customers. To address this demand, MSC added a substantial number of second-hand vessels to its fleet, resulting in a 2.6% increase in the company's EEOI (MSC, 2020 and 2021). Additionally, the increase in the use of exhaust gas cleaning system (EGCS) installations due to the higher number of MSC vessels contributed to the increase in the EEOI. Although EGCS installations help to reduce air pollution, they decrease vessels' energy efficiency, leading to higher CO_2 emissions (MSC, 2021). Similarly, Maersk also experienced an increase in its EEOI of 6.9% from 2020 to 2021, which was due to the disruption to the global supply chain triggered by the COVID-19 pandemic (Maersk, 2020 and 2021). The disruption caused delays in shipping schedules, forcing vessels to sail at maximum speed to meet the increased shipping demand in 2021[15] (Maersk, 2021b). Additionally, the disruption resulted in delayed deliveries of perishable goods, which in turn required reefer containers to work overtime to protect delayed items (Maersk, 2021a). These actions resulted in increased ship fuel consumption and emissions from Maersk's fleet. Therefore, despite the efforts of MSC and Maersk to reduce their carbon footprints, we find that the annual average CO_2 emissions per distance for both companies increase significantly from 2020 to 2021. The COVID-19 pandemic has presented new challenges to the shipping industry, and the industry needs to develop innovative solutions to reduce its emissions while meeting growing customer demands and ensuring supply chain resilience. It is crucial for the industry to continue to adopt sustainable practices, such as the use of alternative fuels, more efficient logistics processes, and greener supply chain management, to achieve sustainability in the future.

(2) CMA CGM and HL

For CMA CGM and HL, their fleets' annual average CO_2 emissions per distance in 2019 and 2020 are significantly different at the 0.05 level, and there is also a significant difference between 2020 and 2021. In addition, for CMA CGM, there is a significant difference between 2018 and 2019; however, for HL, there is no significant difference between 2018 and 2019.

According to the sustainability reports for the 2018–2021 period provided by HL and CMA CGM, both companies have taken measures to reduce their carbon footprints by improving their ships' energy efficiency and reducing fuel consumption (HL, 2018, 2019, 2020, and 2021; CMA CGM, 2018, 2019, 2020, and 2021). They have implemented technical measures such as retrofitting ships and optimizing bulbous bows and propellers, as well as operational measures such as optimizing routes and training

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[15] Maersk's seaborne cargo volumes from 2018 to 2021 are 13,306, 13,296, 12,634, 13,089 FFE ('000), respectively. The value experienced a significant reduction in 2020 due to the global pandemic, but saw a sudden surge in 2021, nearly recovering to the pre-2020 level. "FFE in '000" means that the loaded volume is given in thousands of FFE (forty-foot equivalent) units.

marine personnel. In all three years considered, the annual average CO_2 emissions per distance vary significantly for CMA CGM. However, the performance of HL is slightly different. Specifically, with the exception of 2018–2019, its annual average CO_2 emissions per distance are significantly different among the years considered. Upon examining the fuel consumption per loaded container for each company in 2018 and 2019, we find that CMA CGM reports a 9% reduction in fuel consumption per loaded container in 2019 compared with 2018 (CMA CGM, 2018 and 2019), while HL reports only a 6% reduction in bunker consumption per slot in 2019 compared with 2018 (HL, 2018 and 2019). These results indicate that CMA CGM may have implemented more effective fuel-saving measures or invested more in fuel-efficient technologies than HL during this period.

In 2020–2021, the situation was again affected by the COVID-19 pandemic. Similar to MSC and Maersk, HL and CMA CGM show large increases in their annual average CO_2 emissions per distance from 2020 to 2021. HL's fuel consumption per slot in 2021 remains unchanged from the previous year due to the COVID-19 pandemic's influence; for example, there are longer port stops, delays, and higher ship speeds, as well as the added difficulty of planning due to many ports operating on a first come, first served basis (HL, 2021). Meanwhile, CMA CGM's CO_2 emissions per container transported increase by 3% in 2021 due to the rebound in activity after the COVID-19 pandemic (CMA CGM, 2021). Heavy global port congestion requires vessel fleet adjustments, fleet phase-ins/outs, and speed increases to compensate for waiting times, impacting emission performance.

(3) Hafnia

For Hafnia, the annual average CO_2 emissions per distance in 2019 and 2020 are significantly different at the 0.05 level, but no significant difference is observed between 2018 and 2019 or between 2020 and 2021.

From 2019 to 2020, Hafnia demonstrates a significant reduction in annual average CO_2 emissions per distance, with its EEOI decreasing from 11.8 to 10.9 (Hafnia, 2019 and 2020), highlighting the company's commitment to reducing emissions and enhancing its energy efficiency through strategic initiatives. Hafnia adopts a data-centric approach and implements a computerized performance system across its fleet to optimize vessel performance and ensure regulatory compliance (Hafnia, 2019). This system supports weather routing, speed optimization, and communication with onboard teams for training purposes. Additionally, Hafnia focuses on upgrading its fleet and enhancing its efficiency in various ways, such as increasing propeller diameters, installing ballast water treatment systems, and utilizing a fixed online performance measurement indicator system to optimize the main engine's fuel consumption. These efforts are complemented by other measures, including intermittent dry docking and opportunistic fleet renewal, demonstrating Hafnia's efforts to achieve its emissions reduction goals; as a result, its annual average CO_2 emissions per distance decrease significantly in 2020.

In contrast to other shipping companies, Hafnia mainly operates oil and chemical tankers, which were less affected by the COVID-19 pandemic than container ships. Oil and chemical tankers transport essential goods that are critical to many industries, meaning that the demand for these goods remained relatively stable during the pandemic, enabling Hafnia to sustain its operations. Furthermore, oil and chemical tankers typically have simpler routes, making fewer stops and being less affected by disruptions such as port closures. For example, a typical oil tanker that carries crude oil from the Middle East to Japan first passes through the Strait of Hormuz from Ras Tanura Port in Saudi Arabia. It then enters the Indian Ocean, navigates through the Strait of Malacca and the Strait of Singapore, and sails across the Pacific Ocean. Finally, it reaches Tokyo Bay. Along this route, the oil tanker only visits major ports, such as Jebel Ali Port and Fujairah Port in the Middle East, Port Klang and the Port of Singapore in Southeast Asia, and the Yokohama Port in Japan. Using the MRV data, we calculate the mean values of the annual time spent at sea and the annual sailing distances of oil tankers, chemical tankers, and container ships visiting EU ports from 2018 to 2021. We find that the mean value of the annual time spent at sea for container ships is 17.0% and 23.9% higher than that of chemical tankers and oil tankers, respectively, while the mean value of the annual sailing distance of container ships is 58.9% and 80.0% higher than that of chemical tankers and oil tankers. Therefore, oil and chemical tankers transport goods over shorter distances than container ships, which spend more time at sea; they were therefore exposed to more risks during the pandemic. As a result of Hafnia's strategic initiatives and the nature of its operations, its EEOI for 2021 is improved by 2% compared with 2020 (Hafnia, 2021). Therefore, Hafnia's annual average CO_2 emissions per distance do not change significantly from 2020 to 2021, while the annual average CO_2 emissions of other shipping companies increase due to COVID-19.

5. Policy recommendation and management strategies

5.1 Facilitating collaboration and knowledge sharing

The MRV system could serve as a platform to promote collaboration and knowledge sharing among shipping companies, industry stakeholders, and policymakers. For example, the EU can assess the energy performance of shipping companies based on their energy efficiency indicators reported in the MRV system. Based on the assessment results, the EU can identify the shipping companies that exhibit the most effective green shipping practices and invite them to share details of the retrofitting measures and clean technologies adopted. By facilitating such collaboration and knowledge sharing, the MRV system can promote the exchange of best practices in energy efficiency, emissions reduction, and the adoption of cleaner technologies. Shipping companies can learn about various successful emissions reduction experiences via this platform, helping them to select the most suitable practices in vessel operations, such as optimizing routes, reducing speeds, and implementing weather routing. This can help them to reduce their fuel consumption and emissions while maintaining competitiveness in the industry. In addition, the EU can organize workshops, webinars, and conferences to establish a common understanding of the challenges and opportunities among shipping companies, driving collective action toward a more sustainable shipping industry. This collaborative approach can also foster innovation and enable stakeholders to leverage one another’s expertise and resources, ultimately leading to more effective climate action.

5.2 Supporting the development of green shipping infrastructure

Beginning in at least 2020, many shipping companies set ambitious goals to achieve carbon neutrality by 2050 by reducing their carbon footprints. For instance, in 2020, CMA CGM established this as its new objective. In pursuit of carbon neutrality, shipping companies are exploring alternative fuels such as LNG. Despite its potential to reduce GHG emissions, challenges in adopting LNG remain. A key difficulty is the lack of developed infrastructure, such as bunkering facilities and port storage terminals, making it difficult for companies to ensure fuel availability. Additionally, the retrofitting of vessels for LNG storage and handling can be complex and costly, possibly deterring some companies from adopting LNG-powered ships. Given these challenges, it is vital for the EU to support green shipping infrastructure development by investing in the expansion and modernization of LNG facilities and considering financial incentives, such as grants, tax breaks, or subsidies, to encourage investment in LNG-powered vessels and retrofitting projects (Schroer et al., 2022). Another crucial aspect of green shipping infrastructure development is investing in onshore power supply facilities at ports (Wang et al., 2021). These facilities enable ships to switch off their engines while at berth, reducing emissions and contributing to improved air quality in port areas. By providing access to onshore power, the EU can further support shipping companies in their efforts to reduce their emissions and achieve their carbon neutrality goals by 2050.

5.3 Encouraging more accurate emissions monitoring methods

Although method A (BDN and the periodic stocktakes of fuel tank) is the most widely used approach to monitoring emissions in vessels calling at EU ports, there are three alternative methods that can provide higher levels of accuracy. To encourage the adoption of these more accurate methods, i.e., methods B (bunker fuel tank monitoring on board), C (flow meters for applicable combustion processes), and D (direct CO_2 emissions measurements), EU governments can implement a range of incentives for shipping companies. One approach is to offer reduced port fees for vessels utilizing more accurate monitoring methods, which can serve as a financial incentive for companies to invest in more accurate monitoring systems. Another approach is to provide preferential berthing arrangements for ships that use more accurate monitoring methods, such as offering priority access to berths, reducing waiting times, or even reserving berths for these ships. This can help shipping companies to save time and reduce their operating costs, making the adoption of more accurate monitoring methods more appealing. Furthermore, the EU can provide support for the implementation of the three alternative methods, such as offering training, resources, and expert guidance to help companies to navigate the process of selecting and implementing more accurate monitoring methods. By implementing these incentives and supporting the adoption of more accurate fuel consumption and emissions monitoring methods, EU governments can help to improve data reliability in the shipping industry, leading to improved environmental performance and more effective regulatory oversight.

6. Conclusion and future work

The shipping industry contributes considerably to global GHG emissions, making it essential to identify effective strategies to reduce the impact on the environment. The EU has set ambitious goals regarding the reduction of shipping-related GHG emissions, and it has implemented an MRV system for large ships (more than 5,000 gross tonnage) calling at EU ports to gather information related to their CO_2 emissions and energy efficiency. The MRV system has been operating for five years, and four years of MRV data have been accumulated as of May 2023. However, the MRV data have not been fully analyzed, particularly in terms of the temporal trends of key parameters in the MRV reports and the emission performance of shipping companies during the MRV implementation period.

By addressing these gaps, this study conducts an analysis of the MRV data from 2018 to 2021. We first analyze the trends in the ship's basic profile in the MRV system. We identify a decline in the number of ships across different types between 2019 and 2020, revealing that passenger ships were the most influenced by the COVID-19 pandemic. We also examine the top 10 flag states in the MRV system, finding that China, Japan, and Greece are absent, despite being in the top 10 in terms of the total number of registered vessels. This discrepancy could be due to the MRV system's focus on ships over 5,000 gross tonnage, as these countries have comparatively fewer ships of this size. Second, the trends in ship emissions monitoring methods and results are analyzed. We find that method A (BDN and the periodic stocktakes of fuel tank) is the most prevalent during 2018–2021, accounting for over 40% of usage, due to its simplicity and cost-effectiveness. We also calculate the mean and median values of annual fuel consumption and CO_2 emissions, which demonstrate a decreasing trend. We also observe a significant decrease in the use of heavy fuel oil in 2020, alongside a surge in light fuel oil consumption. These findings highlight the impact of more stringent emissions regulations on the shipping industry. Third, we analyze the trends in ship energy efficiency. We categorize ships according to the time-varying characteristics of their EEDI, discovering that nearly 92% of the ships exhibit constant values from 2018 to 2021. A similar trend is observed with the EIV, where 71% of the ships exhibit consistency during this period. The reason for these findings is that the EEDI and EIV are determined by vessel design parameters and energy-efficient technologies, which remain relatively fixed in the short term.

Furthermore, the case study of five shipping companies evaluates their carbon emission performance and highlights the impact of the COVID-19 pandemic on maritime transport. The Wilcoxon signed-rank test is adopted to examine whether there is a significant difference in the annual average CO_2 emissions per distance of these companies for two consecutive years. The results show that MSC, Maersk, and CMA CGM experience a significant decrease in annual average CO_2 emissions per distance between 2018 and 2019, due to the implementation of technical measures, such as retrofitting ships and optimizing bulbous bows and propellers. However, the COVID-19 pandemic in 2020 led to significant increases in annual average CO_2 emissions per distance for all companies except Hafnia, as vessels sailed at higher speeds to compensate for lost time and delays. Compared with other shipping companies, Hafnia’s operations were less affected by the COVID-19 pandemic, as it primarily operates oil and chemical tankers, which are less susceptible to disruptions. This study highlights the need for the shipping industry to develop innovative solutions to reduce emissions while meeting growing customer demands and ensuring supply chain resilience.

The findings of this study provide valuable insights for policymakers and industry stakeholders on the effectiveness of the MRV system in promoting decarbonization in the shipping industry. Based on these findings, we offer several policy recommendations and management strategies, such as facilitating collaboration and knowledge sharing among shipping companies, investing in green shipping infrastructure development, and encouraging the adoption of accurate fuel consumption and emissions monitoring methods. These measures could help to improve the MRV system and promote a more sustainable shipping industry in the EU and around the world, ultimately helping to achieve emissions reduction targets.

To further enhance our understanding of carbon emissions of vessels calling at the EU ports and enlighten more effective strategies for reducing its impact on the environment, future work can focus on two key aspects. First, by combining automatic identification system (AIS) data and MRV data, researchers can examine vessel stops at different ports to estimate carbon emissions associated with each port. This analysis can help identify high-emission ports and guide the development of targeted emission reduction strategies. In addition, AIS data can be combined with vessel characteristic data to explore the relationship between factors such as vessel type, age, size, and the spatial distribution of carbon emissions. This helps identify the carbon emission characteristics of specific vessel types or regions, providing guidance for targeted emission reduction measures. Second, we only select five word-leading shipping companies to investigate the emission performance of shipping companies during the MRV implementation period. While these companies have demonstrated efforts towards emission reduction, it should be acknowledged that the shipping companies with vessels visiting EU ports are diverse, encompassing a wide range of vessel types and sizes. Therefore, future research should include a broader range of shipping companies with ships visiting EU ports to gain a more comprehensive understanding of their emission profiles and optimization practices.

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